Modeling the thermal X-ray emission around the Galactic center from colliding Wolf-Rayet winds

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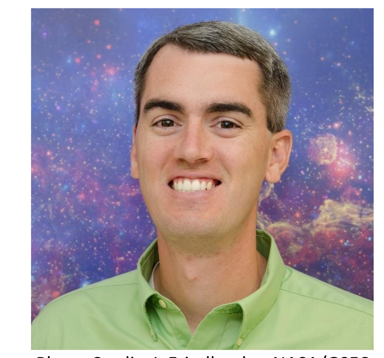

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Abstract

The Galactic center is a hotbed of astrophysical activity. Powering these processes is the injection of wind material from 30 massive Wolf-Rayet (WR) stars orbiting within 12"of the super-massive black hole (SMBH). Hydrodynamic simulations of such colliding and accreting winds produce a complex density and temperature structure of cold wind material shocking with the ambient medium, creating a large reservoir of hot, X-ray-emitting gas. A Chandra X-ray Visionary Program observed the Galactic center for 3 Ms and resolved this diffuse emission. This work aims to confront these Chandra observations by computing the X-ray emission from the hydrodynamic simulations of the colliding WR winds, amid exploring a variety of SMBH feedback mechanisms. The major success of the model is that the spectral shape from the 2"-5" ring around the SMBH matches the observation well. This naturally explains that the hot gas comes from colliding WR winds, and that the wind speeds of these stars are in general well constrained. Additionally, the model flux in this ring and over the 6" images of 4-9 keV is only 2.2x lower than the observations, with stronger feedback mechanisms leading to weaker X-ray emission since more hot, X-ray-emitting gas is cleared from the spherical r < 12” simulation volume. Increasing the WR mass loss rates within their uncertainty will resolve this discrepancy, as well as possibly adding more gas into the simulations, such as from the O stars and their winds, so the adiabatic WR shocks occur closer to their stars, thereby becoming brighter in X-rays.

Intro 1: X-ray Observations (Wang+13)

- Chandra X-ray Visionary Program (PI F. K. Baganoff) observed Galactic center for 3Ms
- Observed flaring and quiescent states

This work: model 2.78Ms of quiescent observations of non-SMBH emission

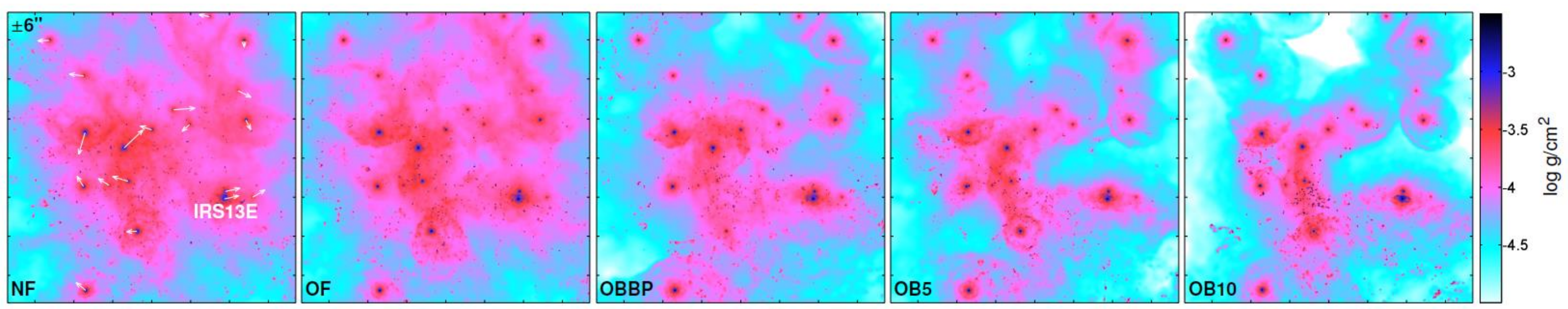
- Intensity maps: spatially resolved 4-9 keV emission from central ±6” (excluding SMBH)
- Spectra: ring from 2”-5” around SMBH

Intro 2: Hydrodynamics (Cuadra+08,15)

- Model orbit and winds of 30 WRs within 12” of SMBH (1”≈ 0.04pc) over 1100 yrs
  - Stars eject wind material
  - SMBH accretes material
- Initial condition: N-body calculation to determine location of stars 1100 yrs ago
- Used Gadget-2, a smoothed particle hydrodynamics (SPH) code

Feedback models

- NF: no feedback
- OF: outflow from SMBH, $\dot{M}_{\rm out}=\dot{M}_{\rm in}$, v=10,000 km/s
- OB: outburst from SMBH occurring 400-100 yrs ago, $\dot{M}_{\rm out}=10^{-4}\,M_{\rm sun}$/yr
  - OBBP: bipolar flow with a 15° half-opening angle and v=5,000 km/s
  - OB5: spherical flow with v=5,000 km/s
  - OB10: spherical flow with v=10,000 km/s

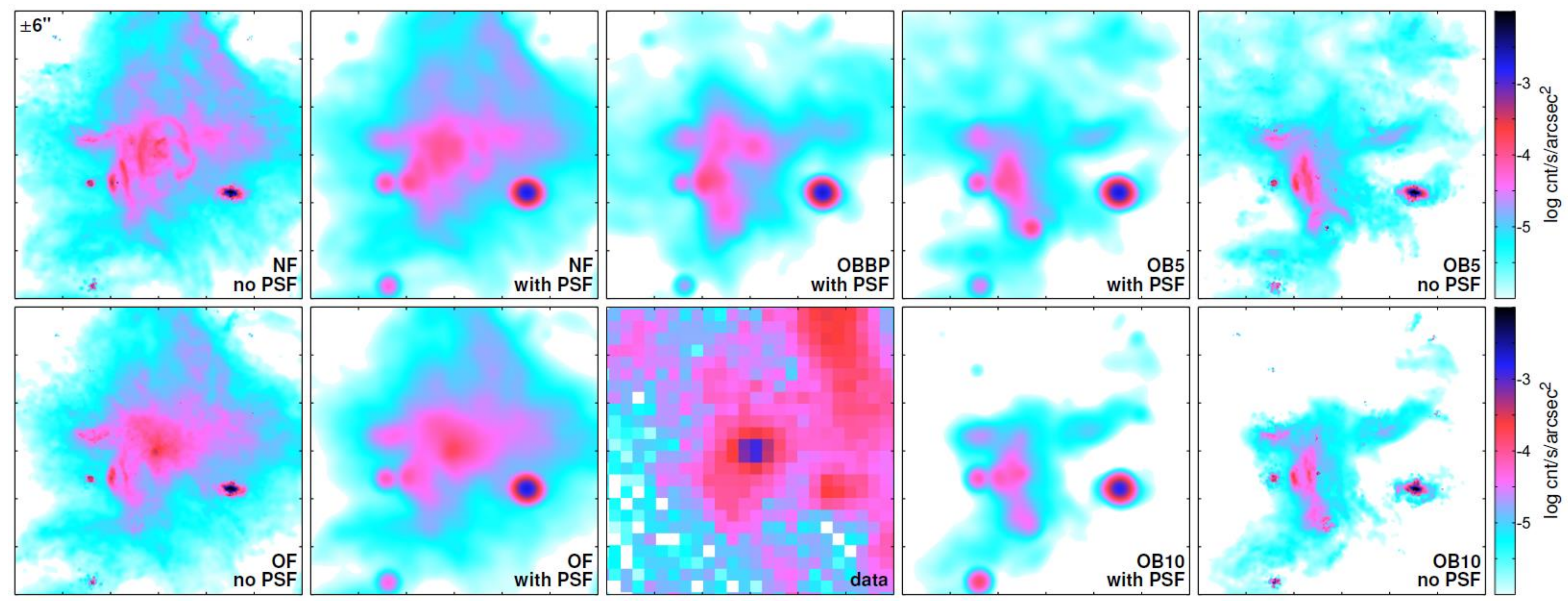


Column density of the various hydrodynamic models at the present day. The images are centered on the SMBH and ±6” in size. The left image shows the motion of the stars. The feedback strength increases rom left to right, as shown by the decreasing amount of material.

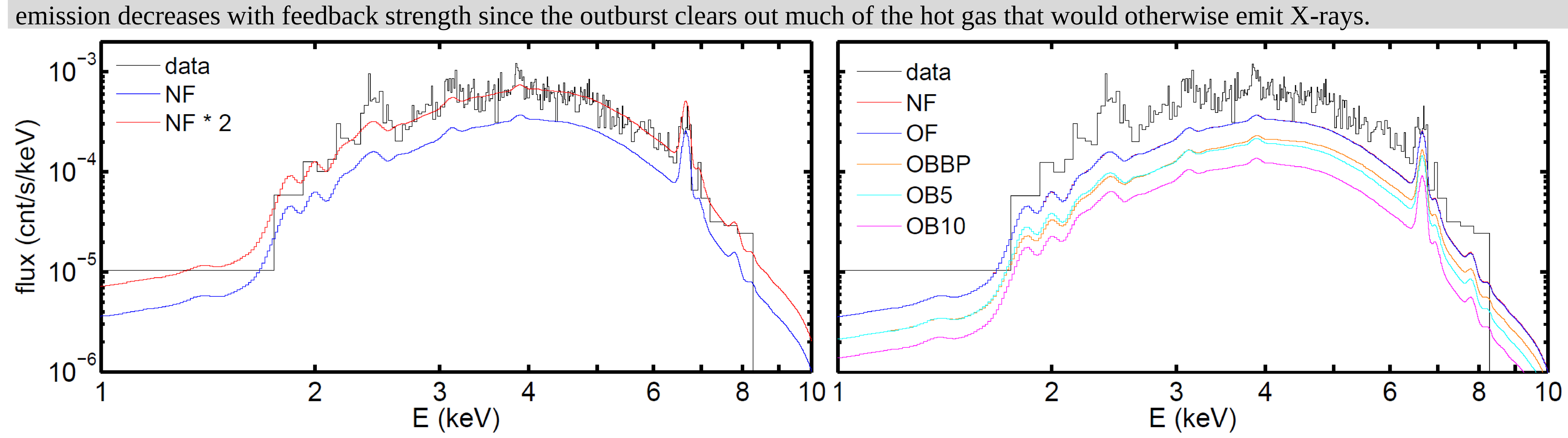
This work: X-ray Calculation (Russell, Wang & Cuadra 16)

- Synthesize thermal X-ray emission from density and temperature structure of hydrodynamic models
- Solve formal solution to radiative transfer
  - Basis is SPH visualization code SPLASH (Price 2007)
  - Low optical depths, so done in optically thin limit: $I_E(x,y)=e^{-\tau_E^{ISM}}\int j_E(x,y,z)\,dz$
- Perform calculation on 500x500 $\{x,y\}$ grid over ±7.5”
  - Obtain 0.3-12 keV spectrum for each pixel
- Fold through ACIS-S/HETG 0th-order response function
- Fold through Chandra PSF (we use 0.5” FWHM Gaussian)
- Emissivity $j_E=n_e n_i \Lambda(E,T)$
  - n_e, n_i: number density of electrons and ions
  - $\Lambda(E,T)$: emission for gas parcel of given energy E and temperature T according to VVAPEC model (Smith+01) obtained through XSpec (Arnaud 96)
    - Abundances: use WC7 (Crowther 07) for all WC stars, WN8 (CMFGEN website model) for WN8-9 and Ofpe/WN9 stars, and WN6 (Onifer+08) for WN5-7 stars
- ISM absorption: $\tau_E^{ISM}=\kappa_E^{ISM} n_H m_p$ (m_p is proton mass)
  - κ_E^{ISM} from TBabs (Wilms+01)
  - n_H is free parameter, determined by fitting spectra

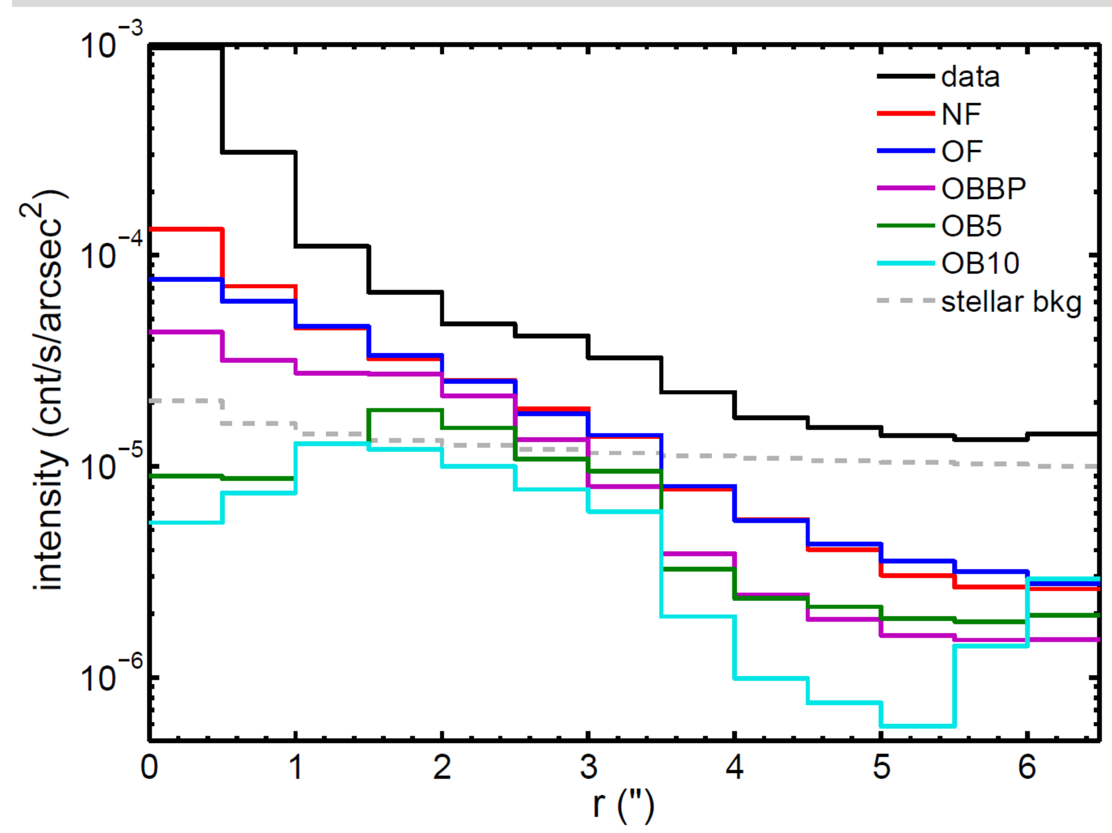
Results



Intensity maps of the 4-9 keV ACIS-S/HETG 0th-order X-ray emission comparing the various models to the observation. The inner 5 model panels are directly comparable to the observation, while the outer 4 panels show the model X-ray calculation prior to PSF folding. The X-ray emission decreases with feedback strength since the outburst clears out much of the hot gas that would otherwise emit X-rays.



Spectra of the ACIS-S/HETG 0th-order X-ray emission from the 2”-5” ring around the SMBH comparing the various models to the observation. The best model is a factor of ~2 below the observation, but the spectral shape well matches the observation, indicated by the red “NF*2” curve in the left panel. The right panel shows the spectra for all models. Their shapes are similar, and their flux follows the trend of the above figure: stronger feedback leads to weaker thermal X-ray emission.



Radial intensity profiles of the ACIS-S/HETG 0th-order X-ray emission from the SMBH comparing the various models to the observation. This shows the stellar background from CVs, based on Chatzopoulos+15, which is subtracted from this data curve and the data intensity map. Over the 2”-5” region, the best model is ~2.4x lower than the observation.

Discussion

- ISM absorbing column: Spectra yields n_H=1.3e23cm^{-2}, similar to n_H=1.66e23 cm^{-2} from modeling SMBH spectra (Wang+13)
- IRS13E cluster: all models have ~2.5x too much X-ray emission → decrease one/both winds
- Diffuse emission: spectra is ~2x too low, intensity maps are ~2.4x too low → mean is ~2.2x too low
  - Within error of mass loss rates stated in Martins+06

Conclusions

- Diffuse thermal emission comes from shocked WR wind material
  - Model shape matches observation well
  - Discrepancy in overall emission level explained by mass-loss rate uncertainties
- Strong feedback models ruled out since X-ray emission is too low

Future Work

- Incorporate O stars/winds, which will increase X-ray emission,
- Incorporate S stars/winds, which will alter SMBH accretion flow
- Add ‘mini-spiral’, which might constrain gas flowing away from SMBH

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